Climate regimes on terrestrial planets within a hierarchy of dynamical models

Conference or Workshop Item

CLIMATE REGIMES ON TERRESTRIAL PLANETS WITHIN A HIERARCHY OF DYNAMICAL MODELS P. L. Read[1], S. R. Lewis[2], J. Mendonca[1], L. Montabone[1,3], D. P. Mulholland[1], T. Ruan[1] and Y. Wang[1], [1]Atmospheric, Oceanic & Planetary Physics, Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, UK (email: p.read1@physics.ox.ac.uk); [2]Department of Physical Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK (s.r.lewis@open.ac.uk); [3]Université Paris VI, Laboratoire de Météorologie Dynamique - Tour 45-55, case courrier 99 – 4, place Jussieu, Paris, France.

Introduction: It has long been argued[1] that "the central scientific problem concerning the global circulation of…[a planetary] atmosphere is that of predicting from the laws of classical physics that…[it] is necessarily organized as it is", and that "research toward a solution must, of necessity, include systematic quantitative investigations of many different but related fluid-dynamical systems".

The Solar System presents us with around eight distinct examples of planetary bodies with substantial planetary atmospheres, of which four are terrestrial-style planets or moons. These atmospheric systems are now being studied in increasing detail from spacecraft such as *Cassini, Venus* and *Mars Express*, *Mars Reconnaissance Orbiter* and a wealth of other missions. They are also being modelled with increasing sophistication using extensions of numerical techniques previously pioneered for the Earth's weather and climate. These approaches are providing an increasingly clear picture as to how their global circulations are organized in a climatological sense.

However, the trend towards the development of sophisticated, physically-based, quantitatively accurate and realistic global circulation models for planets such as Earth, Mars and Venus (as necessary to enable close comparison of model predictions with measurements) can tend to obscure and impede a fundamental understanding of the physics underlying the gross features of the climate and circulation of such planets. Such an understanding is becoming of increasing importance in the context of extra-solar planets, for which detailed measurements and observations are likely to appear only gradually as astronomical instrumentation develops. For such questions, it is clear that a full hierarchy of atmospheric models is crucial, ranging from fully sophisticated GCMs through to analytical and numerical 'toy models'.

Key questions: In this presentation, I will focus on reviewing examples of some of the most fundamental questions concerning our understanding of the climate and circulation of the Solar System planets:

- Why do the atmospheres of slowly-rotating planets (Venus, Titan) strongly super-rotate relative to their underlying planet? Do Venus and Titan super-rotate for the same reason? Is this generic behaviour for slowly rotating planets?
- Why are baroclinic weather systems on Mars significantly more coherent and regular than on Earth? Does this mean they are more predictable in a deterministic sense?
- Why does the Earth sometimes have ~two distinct zonal jet maxima in each hemisphere but Mars, Venus and Titan do not?

We will explore these questions in the context of both full-physics GCMs *and* simpler, more generic dynamical models. This approach is crucial to the elucidation of what factors are *essential* from those that are merely *incidental* to the problem in question.

Dimensionless parameters: We also focus attention on what may be the most important and fundamental (dimensionless) parameters that determine what kind of climatological circulation regime may be observed and how circulation variables might scale with external parameters. By direct analogy with laboratory experiments on rotating, stratified flow[1,2], we identify the thermal Rossby number, Θ, defined by

$$\Theta = \frac{R\Delta\theta_y}{\Omega^2 a^2} \approx \frac{U}{\Omega L}, \qquad (1)$$

(where g is the acceleration due to gravity, R the gas constant, Ω the angular velocity of rotation, a the planetary radius and $\Delta\theta_y$ a measure of equator-pole temperature contrast; U and L are respectively typical horizontal velocity and length scales) as the most significant parameter, enabling, for example, an unambiguous definition of 'slowly' and 'rapidly' rotating planets (for which $\Theta >> 1$ or $<< 1$ respectively). But others will be briefly discussed with a view to constructing a more complete and 'universal' parameter space.

Super-rotation on Titan and Venus: The atmospheres of Titan and Venus are both observed to rotate several times more rapidly than the underlying solid planet (around 60 times in the case of Venus). This was mysterious for many years, although a number of possible mechanisms were suggested e.g. based either on the interaction of zonally-symmetric

Hadley circulations with barotropically unstable eddies [3], or breaking and dissipating thermal tides [4]. More recently it has proved possible to reproduce such strongly super-rotating circulation patterns in GCMs either with highly simplified diabatic forcing or using full representations of radiative transfer, suggesting such super-rotation is a universal phenomenon for planets for which $\Theta >> 1$. Interestingly, the former simulations (for Venus) have tended to favour one mechanism whereas the current generation of full-physics GCMs tends to favour the latter. For Titan, however, diurnal thermal tides are much less likely to play a dominant role (see also the presentations by Lewis et al. and Mendonca et al. at this meeting).

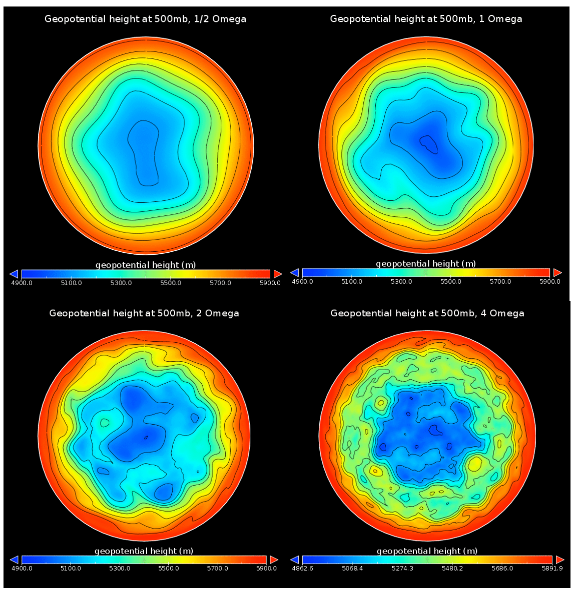

Figure 1: Geopotential height field snapshots at 500 mb of circumpolar flow in SGCM simulations at $\Theta = 0.3$ (top left), 0.08 (top right), 0.02 (bottom left) and 5×10^{-3} (bottom right), illustrating regular baroclinic transient waves at $\Theta \geq 0.2$ and multiple jet formation for $\Theta \leq 0.05$.

Regular & irregular waves on Mars & Earth: Since the early Viking Lander missions to Mars, it has been noted that baroclinic transients on that planet appear to be much more coherent in time and space than on the Earth[5], where transients are highly chaotic and individual features are predominantly short-lived. As long ago as the mid-1980s, the Martian baroclinic wave regime was compared speculatively with the distinctive regular wave regime found in rotating annulus laboratory experiments[6]. More recently, varous kinds of simple GCM have demonstrated similar trends, with highly regular waves appearing in each hemisphere under conditions where $1 \geq \Theta \geq 0.2$ (see Fig. 1a-b). The dynamical mechanisms behind this near-monochromatic spatial wavenumber selection and steady or quasi-periodic equilibration in time will be discussed in light of scale selection in baroclinic instability and the role of damping effects.

Zonal jets in planetary atmospheres: The sub-tropical zonal jets in the atmospheres of Earth and Mars occur at the poleward edge of the main Hadley circulation and results mainly from angular momentum transfer within the thermally-direct, tropical Hadley flow. Additional jet-like structures may also appear, however, that owe their existence to nonlinear interactions with active baroclinic eddies[7]. This appears to be another generic dynamical regime for planetary atmospheres, occurring for $\Theta \leq 0.05$ (such that $(U/\beta)^{1/2} << a$; which is marginally the case only for Earth among Solar System terrestrial planets – see below). It results in the formation of one or more zonal jets parallel with the sub-tropical jet, associated with additional trains of wave-like, baroclinically active eddies (see Fig. 1c-d).

The dynamical mechanisms behind this production of sustained patterns of multiple jets and the factors determining the preferred scales of jets and eddies are surprisingly subtle and seem to result[7] from highly anisotropic transfers of kinetic energy between different scales of motion. The possible relationship between these processes and more well known inverse energy cascades will be discussed (this problem is also currently the subject of an ongoing study team activity at the International Space Sciences Institute in Bern, Switzerland).

As an intriguing final remark, the location of the Earth in parameter space at $\Theta \leq 0.1$ suggests that its atmosphere lies close to a bifurcation leading to the first appearance of an eddy-driven zonal jet in addition to the thermally-driven sub-tropical jet prevalent in other Solar System terrestrial planets.

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